Compact Ocean Models Enable Onboard AUV Autonomy and Decentralized Adaptive Sampling

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LONG-TERM GOALS

Improve synoptic observations and enhance ocean prediction through development of new capabilities for persistent underwater ocean surveillance.

OBJECTIVES

Multi-platform ocean observing systems are typically centrally controlled from shore limiting their ability to adapt to new observations which would inform more effective sampling strategies.
Our objectives:

1. Enhance the ability of mobile agents to respond adaptively by providing them with a synoptic realization of the environment in the form of compact models of the observed ocean, similar to [*Frolov*, 2007; *Frolov et al.*, 2009; *van der Merwe et al.*, 2007a].
2. Develop compact representation of the ocean models that can be economically computed or transmitted onboard of an AUV.
3. Develop algorithms for adaptive planning of AUV surveys.
4. Validate the developed compact ocean models and onboard planning algorithms in a vehicle simulation environment for Monterey Bay.

APPROACH

Numerical models like ROMS and NCOM provide increasingly realistic simulations of ocean environment, however their complexity and computational cost of simulations make impossible the use

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of these models in onboard AUV planning of adaptive surveys. Our approach is based on development of compact model surrogates and reduced-dimension data assimilation algorithms (similar to [*Cane et al.*, 1996; *Frolov et al.*, 2009; *Holmes et al.*, 1996; *van der Merwe et al.*, 2007b]) to enable onboard planning of adaptive surveys in a coastal environment.

Under this project we will:

1. Develop a historic simulation of Monterey Bay that can be used to train model surrogates [Shulman].
2. Train model surrogates based on a historic simulation of Monterey Bay [Frolov].
3. Develop data assimilation algorithms similar to [*Nerger and Gregg*, 2007; *Oke et al.*, 2008] that can be used to (a) guide survey design and (b) evaluate survey performance in an OSSE experiment [Frolov, Shulman].
4. Develop and test algorithms for adaptive onboard planning [Frolov, Zhang, Garau].

WORK COMPLETED

1 Model surrogate development:

1.1 We completed a 2 year run of the NCOM based Monterey Bay area model [Shulman et al., 2007; Shulman et al., 2009]. Preliminary analysis of the multivariate EOFs derived from the model run shows feasibility of the model surrogates development

2 Data assimilation system:

2.1 We developed and tested (in a twin experiment) a coupled, reduced order, bio-optical physical data assimilating scheme with the NCOM model coupled to the ecosystem model. The data assimilation scheme is similar to the localized stationary Kalman Filter and uses a multivariate error covariance matrix computed from a historic simulation of the NCOM model of the Monterey Bay.

2.2 We conducted OSSE s(observation system simulation experiments) to study the strength of the multivariate, bio-optical, physical coupling between observed parameters and the model state variables.

3 Path planning:

3.1 We developed an optimal planner for synoptic surveys. Planning algorithm takes in to the account the time-space covariance structure of the sampled field, time-varying currents, and environment-dependant platform propulsion. We implemented two path planning algorithms: genetic algorithm and A* algorithm.

RESULTS

Observation system simulation experiments (OSSEs)

The strength of the multivariate, bio-optical, physical coupling in the model is presented on Figure 1, where on X-axis are observed variables and on Y-axis are the state variables in the coupled dynamical model. The strength of the coupling is expressed as the R^2 statistics (reduction in uncertainty after the observed variable is assimilated) and is color-coded from red (R^2=100%) to blue (R^2=0%). Figure 1 shows that observed optical variables (absorption, backscatter, and Chl-a) are highly coupled to each other and are most informative of phytoplankton stocks in the model. By observing both backscatter

and absorption, it is possible to differentiate between small and large phytoplankton stocks. It is also apparent that zooplankton and nutrient regeneration stocks are least constrained by the available observations.

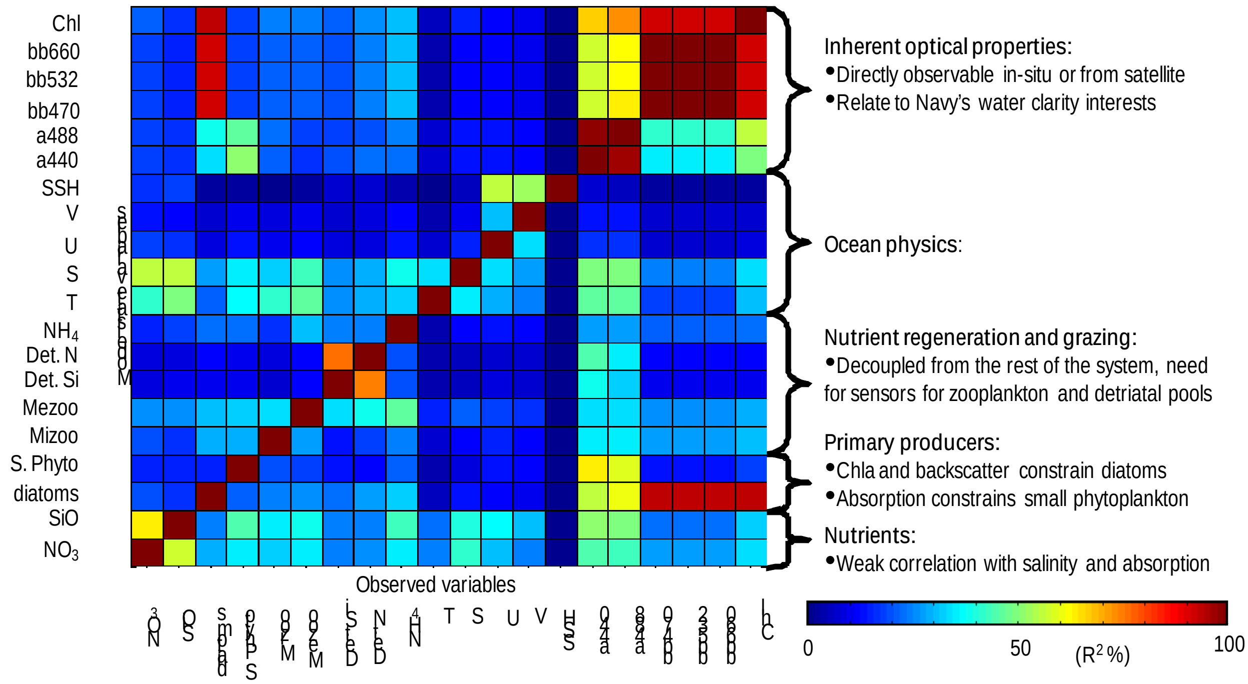

Figure 1: Multivariate coupling between observed variables and state variable in an NPZD model of Monterey Bay. Multivariate coupling was characterized by the state covariance matrix computed from a two-year model run for Monterey Bay. The strength of the coupling was computed assuming that the entire field of the observed variable can be estimated within 10% accuracy.

In the second experiment, we studied the coupling of the surface variables observable with remote sensing to the rest of the water column. The profiles of the R^2 statistics in Figure 2 show that assimilation of IOPs can improve representation of phytoplankton and detritus stocks in the top 20 m of the water column. However, assimilation of physical variables (surface temperature and velocities) has limited multivariate effect on the rest of the variables.

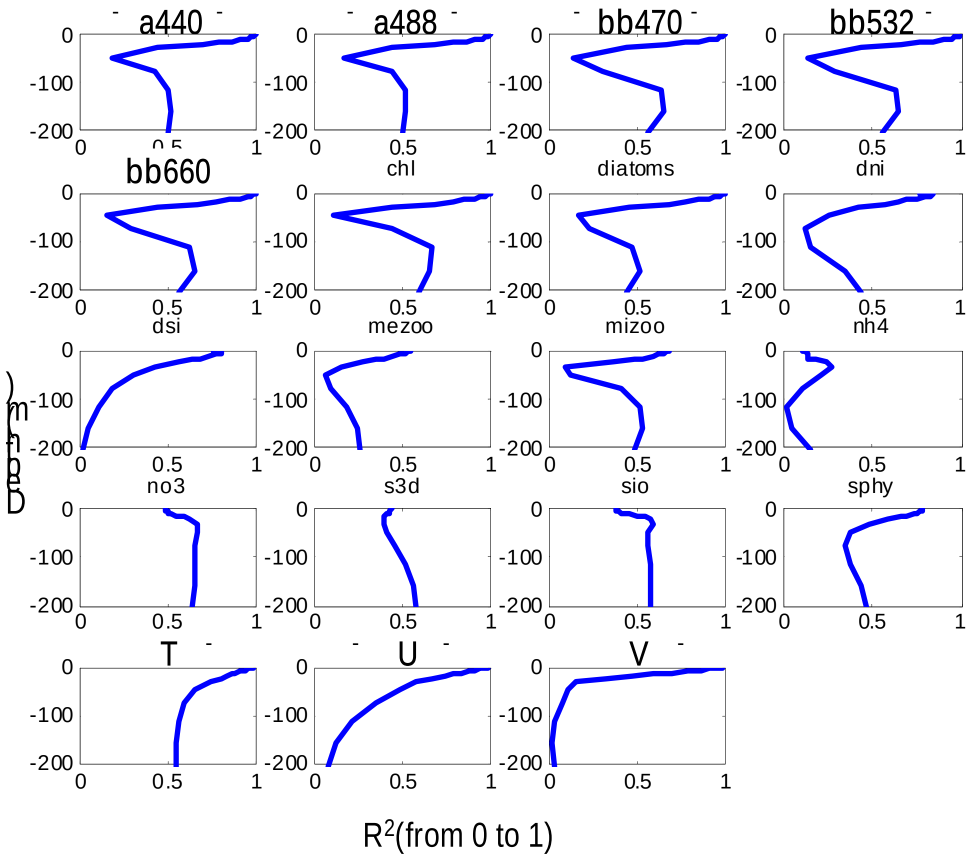

Figure 2: Multivariate impact of assimilating surface absorption, backscatter, temperature, and velocities (highlighted in bold) on the water column parameters. Multivariate covariance was from a two-year model run. Graphs are presented for the location of the M1 mooring.

Our preliminary work on OSSEs elucidate that both absorption and backscatter need to be observed during the October field experiment in order to constrain both small and large phytoplankton stocks in a numerical model. Our analysis also highlighted the need to better characterize zooplankton stocks in an NPZD model, which we plan to accomplish during the field program by collecting acoustic backscatter and particle-size-count data.

Data assimilation twin experiment

To validate the developed data assimilation algorithms, we conducted a twin experiment, where we assimilated backscatter, salinity, and temperature data from a grid of 36 CTD stations. The observational data were extracted from a nature run that assimilated observations of salinities and temperatures from gliders, ship surveys and satellites during the June of 2008, BIOSPACE experiment. In essence, our twin experiment used our new assimilation algorithm to force forecast closer to the analysis fields from an existing operational data assimilation product. The results of the twin experiment in Figure 3 show that our multivariate data assimilation algorithm was successful at reducing errors in large phytoplankton, micro-zooplankton, and in nitrite.

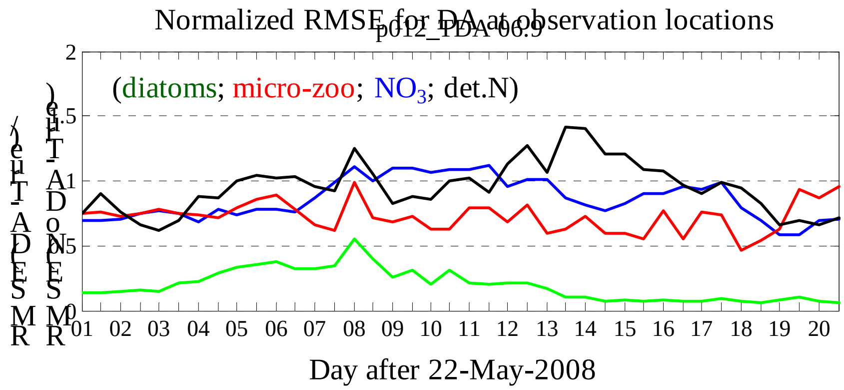

Figure 3: Reduction of errors in a twin experiment. Assimilated variables were temperature, absorption, and backscatter. Error reduction was measured at observation locations for variables that were not assimilated (diatoms, micro-zooplankton and detritus). Errors were normalized by the errors of the non-assimilated run.

Path planner

We have been developing path-planning algorithms that can optimize path plans with resepect to:

a) Synoptic coverage in an area with variable uncertinty (see map in Figure 4.a) and decorrelation scales (see map in Figure 4.b),
b) Limited memory of the observations due to temporal decorrelations in the field (shown in Figure 4.c),
c) Time varying currents, and
d) Possibly varyable propulsion.

We tested the developed algorithms on the realistic dataset of bloom intensity in Monterey Bay (as measured by the climatology of MODIS-FLH) with depth-integrated currents provided by the NCOM model simmulations.

Figure 4 shows the results of the optimal path survey for a glider with the speed of 0.4 m/s (panel d) and an AUV with a speed of 1 m/s (panel e). Both platforms take advantage of the counter-clockwise eddy in the bay and concstruct an optimal path that circles the bay counterclockwise. The faster-moving AUV platform (pannel e) can go further in two days, which results in an optimal path resabling a space-filling curve (pannel e).

Our optimal path planning algorithms will be used to plan surveys with an underpowered sampling platform (Liquid Robotics© Wave Glider) during the joint NRL/MBARI field program in Monterey Bay in October of 2010. Path plans will be optimized to reconstruct the synoptic location of bloom patches in Monterey Bay in presence of strong tidal and sub-tidal currents.

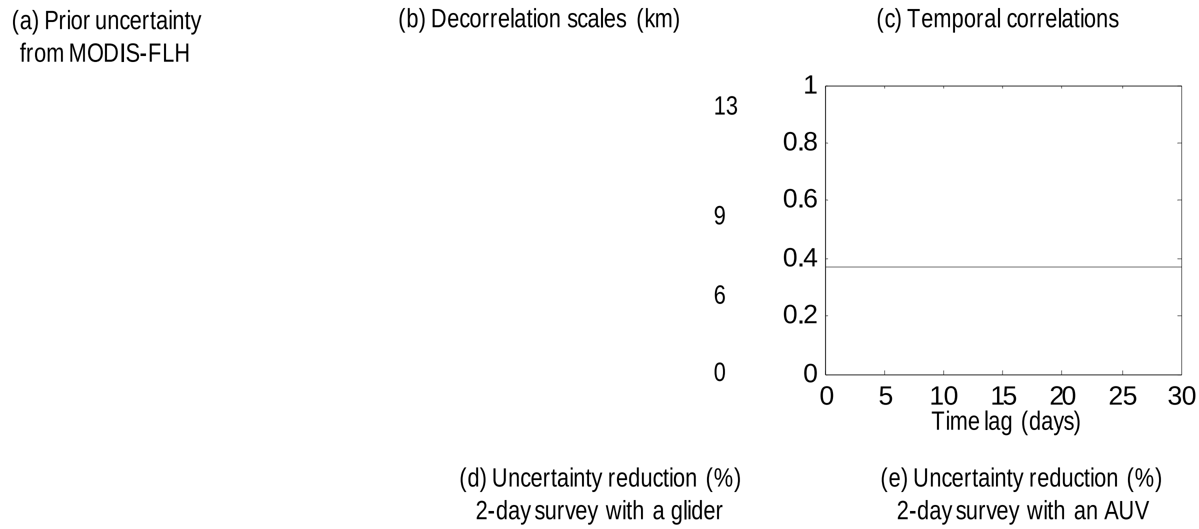

Figure 4: Optimal path planning results. (a) Prior uncertainty (climatological variance of the MODIS-FLH satellite product). Spatial (b) and temporal (c) decorrelation scales used in the calculation. Uncertainty reduction after a 2-day survey with a glider (d) and an AUV (e).

IMPACT/APPLICATIONS

- The proposed development of compact ocean models and adaptive sampling strategies for controlling a new generation of mobile sampling platforms will provide the U.S. Navy with greater situational awareness and a more efficient use of high value observational assets.
- Development of sampling strategies and onboard autonomy algorithms for the new generation of autonomous platforms, such as the MBARI's long-range AUV Tethys [*Bellingham et al.*, 2010] will improve Navy's capabilities in sampling of rapidly changing ocean processes.

RELATED PROJECTS

NRL internal project BIOSPACE: development of data assimilation capabilities was in part supported by the NRL internal BIOSPACE project. BIOSPACE aims at developing tools that can enable prediction of optical properties of the coastal ocean on 3-5 day timescales. In October 2010, BIOSPACE field program is focused on evolution of optical properties of the water in northern Monterey Bay.

MBARI internal project CANON: Field testing of the optimal survey design methods is supported with MBARI internal project CANON. CANON aims at developing new Lagrangian observing systems that can study the dynamics of marine ecosystems by following their evolution in time and space. In October 2010, CANON field program is focused on following emergence, growth, and decay of phytoplankton bloom patches in Monterey Bay.

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